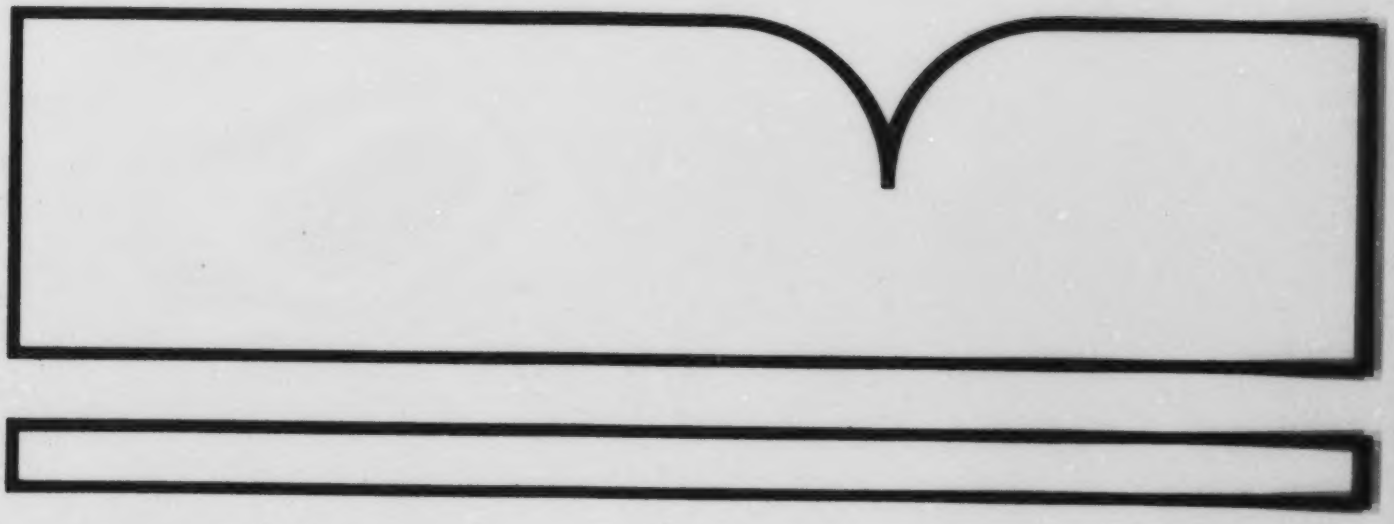
PB84-226950

Terrain Aerodynamics and Plume Dispersion A Perspective View Gained from Fluid Modeling Studies

(U.S.) Environmental Sciences Research Lab.
Research Triangle Park, NC

1984



U.S. Department of Commerce
National Technical Information Service
NTIS

PB84-226950

EPA-600/D-84-205
1984

TERRAIN AERODYNAMICS AND PLUME DISPERSION

A Perspective View Gained from Fluid Modeling Studies

by

William H. Snyder

Meteorology and Assessment Division
Environmental Sciences Research Laboratory
Environmental Protection Agency
Research Triangle Park, NC 27711

ENVIRONMENTAL SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/D-84-205		PB84 226950

4. TITLE AND SUBTITLE	5. REPORT DATE
TERRAIN AERODYNAMICS AND PLUME DISPERSION A Perspective View Gained from Fluid Modeling Studies	1984 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) William H. Snyder[1]	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Environmental Sciences Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711	10. PROGRAM ELEMENT NO. CDTA1D/09 3004 (FY-84) 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Sciences Research Laboratory--RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE EPA/600/09

15. SUPPLEMENTARY NOTES
1. On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

16. ABSTRACT
The results of recent wind-tunnel and towing-tank studies are summarized. These studies were designed to obtain basic physical understanding of flow patterns and diffusion, to provide guidance in locating sources, and to provide "rules-of-thumb" for estimating surface concentrations when a source is located in complex terrain. In the neutral-flow, wind-tunnel studies, the effects of the terrain were evaluated through a terrain amplification factor, A, which is defined as the ratio of the maximum surface concentration that occurs in the presence of the terrain to the maximum that occurs from a similar source located in flat terrain. A's were evaluated for a series of two- and three-dimensional hills of varying slope placed in simulated atmospheric boundary layers. Sources of various heights were placed upstream, at the top, and downwind of the hills. The largest A's were observed for downwind sources with values as large as 15. Flow structure and plume behavior in complex terrain are dramatically altered by the addition of stable stratification. A dividing-streamline concept has been shown to be a useful indicator in determining whether a plume will impact on a hill or surmount the top. When a plume is emitted below the dividing-streamline height and hence impinges on a downwind hill, surface concentrations can be essentially equal to those observed at the plume centerline in the absence of the hill. Favorable comparisons are made between towing-tank simulations and field observations of plumes impinging on a three-dimensional hill. Finally, limitations of the towing tank for simulating strongly stratified flows over two-dimensional hills are pointed out.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
	UNCLASSIFIED	41
RELEASE TO PUBLIC	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

ABSTRACT

The results of recent wind-tunnel and towing-tank studies are summarized. These studies were designed to obtain basic physical understanding of flow patterns and diffusion in complex terrain, to provide guidance in locating sources, and to provide "rules-of-thumb" for estimating surface concentrations when a source is located in complex terrain. In the neutral-flow, wind-tunnel studies, the effects of the terrain are evaluated through a terrain amplification factor, A, which is defined as the ratio of the maximum surface concentration that occurs in the presence of the terrain to the maximum that occurs from a similar source located in flat terrain. Terrain amplification factors were evaluated for a series of two- and three-dimensional hills of varying slopes placed in simulated atmospheric boundary layers. Sources of various heights were placed upstream, at the top, and downwind of the hills. The largest A's were observed for downwind sources; values as large as 10 to 15 were observed for sources downwind of two-dimensional ridges, and values in the range of 5 to 6 were observed for sources downwind of three-dimensional hills. For upwind sources, A-values were typically 2 to 4 for three-dimensional hills and 1 to 3 for two-dimensional ridges. The best source locations were, of course, the hill top, where A's were typically in the range of 0.5 to 1.

The flow structure and hence plume behavior in complex terrain are dramatically altered by the addition of stable stratification. A dividing-streamline concept has been shown to be a useful indicator in determining whether a plume will impact on a hill or surmount the top. Fluid modeling studies have shown the concept to be applicable to a wide range of hill shapes, density profile shapes, wind angles, and in strong shear flows as well. When a plume is emitted below the dividing-streamline height and hence impinges on a downwind hill, surface concentrations can be essentially equal to those observed at the plume centerline in the absence of the hill. Such concentrations are typically 3 to 4 orders-of-magnitude greater than those from plumes in neutral flows.

Comparisons are made between towing-tank simulations and field observations of plumes impinging on a three-dimensional hill. The unsteadiness in wind speed and direction in the field observations was simulated in the tank through a matrix of 18 individual tows at different towing speeds and directions. The resulting superposition of concentration patterns compared quite favorably with the field measurements. Finally, limitations of the towing tank for simulating strongly stratified flows over two-dimensional hills are pointed out.

1. INTRODUCTION

The ability to predict ground-level concentrations of air pollutants released from sources in or near complex terrain is required in order to determine the environmental impact from existing sources, to evaluate alternative new source locations and designs, and to estimate the effects of possible modifications to existing sources. Mathematical models that reliably predict concentrations when plumes are affected by complex terrain are not yet available. Field studies are very expensive and time consuming, and the results are not generally transferable to other sites. Previous wind-tunnel studies on dispersion of effluents from industrial plants located in complex terrain have usually been designed to answer specific questions such as the suitability of a particular plant location or the stack height necessary to avoid downwash; the results have not been generally applicable to other sites.

In the early wind-tunnel studies, care was taken to ensure a uniform wind profile and low turbulence intensity in the flow approaching the model. More recent studies have shown that the effects of shear and turbulence intensity (and scales) in the approach flow can strongly affect the basic flow structure over a model, e.g., the turbulence can move the locations of separation and reattachment points on the lee sides of hills. Hence, in the past 15 years, serious attempt have been made to simulate the atmospheric boundary layer, including stratification, and to conduct "generic studies", wherein idealized terrain features have been used to obtain basic physical understanding. This is contrasted with "engineering case studies", wherein very specific questions are answered with regard to particular installations.

This paper attempts to summarize the results of recent neutral (wind-tunnel) and stably-stratified (towing-tank) studies that were designed to obtain basic physical understanding of flow and diffusion in complex terrain.

These results provide guidance on locating sources in complex terrain as well as "rules of thumb" for estimating concentrations when a source is located in complex terrain. Most of the results and conclusions reported herein are based on studies conducted in the Meteorological Wind Tunnel (Snyder, 1979) and the Towing Tank (Thompson and Snyder, 1976) of the EPA. Each of these studies followed the guidelines of Snyder (1981), but the details may have differed considerably from one study to the next. Direct intercomparisons of the results of these studies are made to obtain a perspective view, but the reader is cautioned to study the original reports in detail before attempting to apply the conclusions to the real atmosphere.

2. NEUTRAL-FLOW WIND-TUNNEL STUDIES

The effects of terrain on the flow can be demonstrated through the deflection of streamlines over and around ridges and hills. For example, the displacement of the mean streamlines determines how near to the surface the centerline of the plume will reach. The convergence and divergence of the streamlines in the directions normal to and, in the case of three-dimensional flows, parallel to the surface affect the plume width (see Hunt, Puttock and Snyder, 1979). If flow separation occurs, the size and shape of the recirculating cavity that ensues and the position of the source with respect to this cavity can be very important in determining subsequent plume behavior.

A simple way to evaluate the effects of terrain on concentration is to calculate a terrain amplification factor A which is defined as the ratio of the maximum surface concentration occurring in the presence of the terrain χ_{mx} to the maximum that would occur from a similar source in flat terrain χ°_{mx} (see Figure 1). This definition is useful only for elevated sources, of course, because for ground-level sources, the maximum surface concentration occurs at the source itself.

Using these ideas, the results of studies using two- and three-dimensional terrain features will be described.

2.1 Two-Dimensional Hills

Numerous studies have been conducted on two-dimensional terrain features: (a) a ramp with a slope of 14° followed by an elevated plateau (unpublished), (b) a bell-shaped hill with a maximum slope of 12° by Courtney and Arya (1980), (c) a steep triangular ridge with a slope of 68° (Arya and Shipman, 1981; Arya et al, 1981), but perhaps the most illustrative is (d) a series of smooth-shaped hills by Khurshudyan et al (1981).

In the latter study, three hill shapes were generated from a set of parametric equations. The aspect ratios (streamwise half-length/height) of the hills were 3, 5 and 8; maximum slopes were 26°, 16° and 10°, respectively. These hills are referred to by their aspect ratios, e.g., hill 5.

Streamlines derived from mean velocity measurements with hot-wire and pulsed-wire anemometers are shown in Figures 2, 3 and 4. No flow separation was observed on the lee sides of hills 8 or 5; however, the pulsed-wire measurements showed that, whereas the mean flow on the lee side of hill 5 was everywhere downstream, instantaneous flow reversals occurred frequently. Indeed, at one position, reverse-flow was observed up to 40% of the time. A large cavity clearly formed on the lee side of hill 3.

From a study of the streamline patterns of Figures 2 through 4 we may anticipate qualitative effects of the terrain on sources placed at various positions with respect to the three hills. For example, consider sources located at the upwind bases of the three hills. Because of the stronger convergence of streamlines (plume centerline closer to surface) upwind of hill 3 (as compared with hill 8) we may expect larger terrain amplification factors (A) there. Because of the divergence of the streamlines downwind of the hill centers, we may expect A's less than 1.0, and smaller values

for the steeper sloped hills. When sources are located at the downwind bases of the hills, we may expect quite different behavior because of the strong differences in streamline patterns. For hill 8 (10° slope), the streamline pattern appears nearly symmetrical fore and aft of the hill center, so that we might at first expect similar terrain amplification factors as found for upwind sources. However, because of the much larger turbulence intensities in the lee of the hill, considerably larger A's were observed there (to be shown later). For low sources located at the downwind base of hill 3 (26° slope), Figure 4 shows that it would be located within the recirculation cavity, and we may, in fact, expect to find the maximum surface concentration upwind of the source. For higher sources (i.e., for sources located on the separation-reattachment streamline), we may expect the plumes to impinge directly on the surface downwind, with very large terrain amplification factors resulting. Because of the strong convergence downwind of the base of hill 5 (16° slope), we may expect large A's for sources located there. These statements, however, are speculative, because we have not accounted for changes in turbulence intensity as effected by the terrain. As we shall see shortly, the statements are generally true, but a few surprises are in store.

Ground-level concentrations (glc's) were measured downwind of sources of various heights located at the upwind bases, the tops, and the downwind bases of the hills. Three sets of glc patterns are compared with those measured over flat terrain in Figures 5, 6 and 7. The source height H_S is half the hill height h in each of these cases, x_S/h is the distance downwind from the source, and χ is the nondimensional concentration, $\chi=CUh^2/Q$, where C is the concentration, U is the free-stream wind speed, and Q is the source flow rate. In Figure 5, the sources were located at the upwind bases of the hills, and the maximum glc's occurred at the tops of the hills in all cases. A's increased from 1.1 to 2.5 as the slope of the hill increased from

10° to 26°. The influence of the recirculating cavity for hill 3 is clearly evidenced by a sharp drop in concentration at the separation point and a secondary peak at the reattachment point.

Figure 6 shows that the amplification factors were less than unity for sources located at the hill tops. The effect of the recirculation cavity is again clearly evidenced for hill 3; effluent entered the cavity near the reattachment point and was transported up the lee slope to the separation point.

Large values of A were observed for all three hills when the sources were at the downwind base locations (Figure 7). For hill 3, the maximum glc was located upwind of the source because of the reverse flow within the cavity. A somewhat surprising result, however, is that the largest A occurred for hill 5, where the mean flow did not separate. As mentioned earlier, due to the intermittent separation, the mean velocity was extremely small at the downwind base (exemplified by the large spacing of streamlines near the downwind base, shown in Figure 3), and, therefore, the local turbulence intensities were extremely large.

Table 1 summarizes the observed terrain amplification factors for the various stacks at the three locations. A maximum A of 15 occurred with a stack of height one-fourth the hill height and located at the downwind base of hill 5. This was due to the very small mean transport but very rapid turbulent transport at that location. A's nearly as large occurred when the source was located near the separation-reattachment streamline, because in this case, the plume was advected directly toward the surface (reattachment point). Upwind sources resulted in terrain amplification factors in the range of 1.1 to 3, with the larger values being observed for the steeper hills. Finally, the hill top source location resulted in amplification factors less than unity, with smaller values being observed for steeper hills.

TABLE 1. TERRAIN AMPLIFICATION FACTORS FOR TWO-DIMENSIONAL HILLS

HILL	H_s/h	A SOURCE LOCATION UPWIND	TOP	DOWNWIND
8	1/4	1.5	0.9	3.4
	1/2	1.1	0.6	3.0
	1	1.5	0.8	2.4
	1-1/2	1.2	0.8	1.7
5	1/4	2.0	0.5	15.0
	1/2	2.0	0.6	8.0
	1	1.7	0.9	5.6
	1-1/2	1.2	1.0	2.9
3	1/4	2.8	0.3	7.5
	1/2	2.5	0.7	6.4
	1	1.8	0.9	10.8
	1-1/2	1.9	0.9	7.8

2.2 Three-Dimensional Hills

Two studies have been conducted to determine the effects of the crosswind aspect ratio of a hill on dispersion from nearby sources. Triangular ridges of different crosswind lengths were constructed by cutting a cone in half and inserting straight triangular sections between the two halves. A sketch of these hills is given and the aspect ratio is defined in Figure 8. The slope of the ridges was 1:2, or 26.5°. Four configurations were used: C2 was the basic cone, C4 and C6 had short and long straight sections, respectively, inserted between the two halves, and CX was a two-dimensional triangular ridge that extended completely across the test section of the wind tunnel.

Snyder and Britter (unpublished) investigated surface concentrations on the ridges resulting from upwind sources. Ground-level concentrations were measured downwind of stacks of height 0, 0.5 and 1 h, with the stacks located 3.7 h upwind of the hill centers. Results for the cone and the two-dimensional ridge are shown in Figures 9 and 10, respectively. For the ground-level source, downwind concentrations were reduced by the presence

of the hills due to the excess turbulence and divergence of the flow around the hills. For the elevated sources, the maximum glc's occurred at the crest or on the lee sides of the hills. The maximum values for the cone were 2 to 3 times those for the two-dimensional ridge and 2 to 4 times those in flat terrain.

Castro and Snyder (1982) extended this study by locating sources at various downwind positions. Flow separation was observed on the lee sides of these hills because of the steep lee slopes and the salient edge at the crests. The shapes of the recirculating cavities were measured with pulsed-wire anemometry. Loci of zero-longitudinal mean velocity are shown in Figure 11. Sources were placed downwind of these hills, with the locations being selected as predetermined fractions of the distances to the reattachment points, x_S/x_R, where x_R is the distance to the reattachment point (both measured with respect to the hill center).

Figure 12 provides a summary of the terrain amplification factors. The largest A's were observed when the effluent was emitted near the separation-reattachment streamline (e.g., $x_S/x_R \sim 0.5$ and $H_S/h \sim 1$). In general, A's increased with an increase in aspect ratio; the largest value of A (= 11) was observed for the two-dimensional ridge.

2.3 Summary for Neutral Flows

The cases discussed above are summarized in Table 2 by listing them in order of decreasing A. From the standpoint of a fixed stack height, it appears that the worst location for a source is just downwind of a two-dimensional ridge and the best is on top of a ridge.

Downwind sources generally result in larger glc's because of the excess turbulence generated by the hills and because the effluent is generally emitted into streamlines that are descending toward the surface. Maximum terrain

TABLE 2. SUMMARY OF TERRAIN AMPLIFICATION FACTORS FOR NEUTRAL FLOW

SOURCE LOCATION	HILL TYPE	A
DOWNWIND	TWO-DIMENSIONAL	10-15
DOWNWIND	THREE-DIMENSIONAL	5-6
UPWIND	THREE-DIMENSIONAL	2-4
UPWIND	TWO-DIMENSIONAL	1-3
TOP	TWO-DIMENSIONAL	0.5-1

amplification factors are considerably larger downwind of two-dimensional hills than those downwind of three-dimensional hills. A probable cause of this effect is that, in three-dimensional flows, lateral and vertical turbulence intensities are enhanced by roughly equal factors, whereas in two-dimensional flows, the lateral turbulence intensities are not enhanced as much as are the vertical turbulence intensities (because of the two-dimensionality). Since the maximum glc depends upon the ratio σ_z/σ_y (Pasquill, 1974), we may expect the A's downwind of two-dimensional hills to be larger than those downwind of three-dimensional hills. Also, the sizes of the recirculating cavity regions of three-dimensional hills are generally much smaller than those of two-dimensional ridges.

With regard to upwind sources, terrain amplification factors are larger for three-dimensional hills because, in such flows, streamlines can impinge on the surface and/or approach the surface more closely than in two-dimensional flows (see Hunt and Snyder, 1980; Hunt, Puttock and Snyder, 1979; Egan, 1975).

3. STABLY STRATIFIED TOWING-TANK STUDIES

Plume behavior in complex terrain is dramatically altered by the addition of stable stratification: plume growth is severly inhibited, possibly

reduced to zero growth (Britter et al, 1983); under strong enough stratification, the flow may have insufficient kinetic energy to overcome the potential energy of the stratification to surmount the hill, so the plume may be forced to impact on the front surface of the hill and travel round the sides (Hunt and Snyder, 1980); yet, under appropriate conditions, the plume may be rolled-up in a free-stream rotor above the hill top or possibly in an attached rotor on the lee side of the hill (Castro et al, 1983). The dividing-streamline concept has been shown to be a useful indicator in determining whether a plume will impact on the windward surface of a hill or surmount the top (Snyder et al, 1984). The dividing-streamline height is applicable to a wide range of hill shapes, density profile shapes, and wind angles, and in strong shear flows as well.

3.1 Dividing-Streamline Height

The basic concept of the dividing-streamline height is that in strongly stratified flows over three-dimensional hills, the flow is composed of two layers. In a lower layer of essentially horizontal flow, the approach flow has insufficient kinetic energy to overcome the potential energy of the stratification to surmount the top. Plumes from upwind sources impinge directly on the hill surface. In an upper layer, the approach flow does have sufficient kinetic energy, so that plumes from upwind sources may pass over the hill top. The depth of the lower layer is the dividing-streamline height, H_D. It is primarily a function of the Froude number, $F = U/Nh$, where U is the approach flow velocity, N is the Brunt-Vaisala frequency, and h is the hill height.

The utility of the two-layer concept arises because the transport and diffusion in each layer may be analyzed quite separately and independently of one another using different but well-established techniques in each layer. In the lower layer, for sufficiently strong stratification ($F \ll 1$), the flow

is approximately horizontal. Outside the wake, the velocity field at height $z < H_D$ is the same as two-dimensional flow about a cylinder. The shape of the cylinder is defined by the contour of the hill at height z. Given this mean flow field and the fact that stable stratification limits vertical diffusion, the calculation of dispersion from a point source at height H_S ($< H_D$) is the same as that from a line source near a cylinder (See Figure 13 and Hunt, Puttock and Snyder, 1979, and Weil et al, 1981).

In the upper layer, buoyancy and inertial forces control the flow as it passes over the hill. The simplest and easiest assumption to make in constructing a mathematical model (and the only one made to date) is that the dividing-streamline surface is perfectly flat, i.e., that the upper- and lower-layer flow regimes are separated by a horizontal plane. As discussed by Snyder and Hunt (1984), a plume released in the upper-layer flow (at H_S) upstream of a hill of height h may be treated like a release from a stack of height $H_S - H_D$ upstream of a hill of height $h - H_D = Fh$, i.e., as if a ground plane were inserted at height H_D. The stratification above H_D, of course, has important influences on the diffusion as well as the vertical convergence and horizontal divergence of streamlines, so that the flow structure over the hill of height Fh must be treated like that with $F = 1$, i.e., the Froude number of the flow over this smaller hill is unity (Bass et al, 1981; Hunt et al, 1984).

3.2 Hill-Surface Concentrations

Snyder et al (1980) and Snyder and Hunt (1984) have shown that when a plume embedded in the lower layer (i.e., released below H_D) impacts on a hill surface, the maximum glc's can be essentially equal to those observed at the plume centerline in the absence of the hill. Plume centerline concentrations for stable plumes are typically 3 to 4 orders-of-magnitude larger than maximum glc's from stable plumes over flat terrain. Hence, the

terrain amplification factor that was used for neutral conditions results in extremely large numbers that would be difficult to interpret, and a new factor A_S is defined for stable flows as the ratio of the maximum observed glc in the presence of the terrain to that observed at the plume centerline at the same downwind distance in the absence of the hill.

3.3 Flat Dividing-Streamline Surface

Snyder and Lawson (1983) conducted a series of towing-tank studies to examine surface concentration patterns resulting from upwind plumes released in the upper layer and, more specifically, to test the adequacy of the assumption of a flat dividing-streamline surface. It was known from laboratory studies that, even well within the lower layer, streamline trajectories are not contained within horizontal planes. On the other hand, concentration measurements on hill surfaces (Snyder and Hunt, 1984) suggested that a flat-surface approximation may yield reasonable estimates. From a practical viewpoint, the mathematical models are vastly simplified if such an assumption yields reasonable estimates of surface concentration. Hence, Snyder and Lawson (1983) attempted to answer the question not from a detailed analysis of the shape of such a dividing-streamline surface, but from the more practical comparison of surface concentration patterns.

In the Snyder and Lawson experiments, linear density gradients were established in the tank and the hill was towed at a speed U such that the Froude number F(=U/Nh) was 0.5 (establishing a dividing-streamline height of $H_D = 0.5$). Effluent was released at a height of 0.6 h and the resulting hill-surface concentration patterns were measured. A second tow was conducted wherein the entire model (hill, baseplate and stack, as a unit) was raised out of the water* to a point where the water surface was precisely

---

*The model is routinely mounted upside-down such that the baseplate is submerged a few millimeters below the water surface. In discussion of flow structure and plume behavior, however, we describe the results as if the model were right-side up.

at the dividing-streamline height, i.e., the water surface was at half the hill height. The model was towed at the same speed as in the full-immersion tows, so that the Froude number of this now half-height hill was unity, and all streamlines passed over the hill top. The flat water surface thus forced a flat dividing-streamline surface. The resulting surface concentration patterns were then compared with the full-immersion patterns to ascertain the effects of a flat dividing-streamline surface.

Figure 14 shows a comparison of the concentration distributions resulting from the full- and half-immersion tows. The plumes were spread broadly to cover essentially the entire surface above half the hill height (the dashed circle on the figure marks half the hill height). The contours on the windward side of the hill are roughly circular, but somewhat elongated in the streamwise direction. In the half-immersion case, no concentrations were observed below half the hill height, of course, because that portion of the model was out of the water. In the full-immersion case, the plume "hugged" the lee side of the hill and was swept to elevations considerably lower than half the hill height.

Figure 15 presents a scatter diagram comparing, on a point-by-point basis, the surface concentrations measured in the half- and fully-immersed cases. Within the region of large concentrations, the two cases compared quite favorably, the half-immersed case yielding concentrations approximately 10 to 20% larger than the fully-immersed case. In the region of low concentration, quite large differences occurred (worst case, a factor of 10). However, a close examination shows that in all cases where the concentrations differed by more than a factor of 2, the sampler locations were very close to half the hill height, i.e., either at 0.505 h or 0.51 h.

These results suggest that the assumption of a flat dividing-streamline surface in a mathematical model is a reasonable approximation to make, at least with regard to predicting the locations and values of maximum concentrations and areas of coverage.

3.4 Comparison with Field Studies

While much has been learned about flow and dispersion under stable conditions, the applicability of towing-tank results to the atmosphere is sometimes questioned. The height of the dividing-streamline is directly proportional to wind speed, and in a towing tank, the wind speed is constant. The unsteadiness of the wind in the field, however, can allow the plume to impact on the front surface at one moment, then sweep it over the top at the next moment. Similarly, a meandering wind will result in a plume being swept from one side of the hill to other, resulting in significant reductions of surface concentration. Carefully designed field studies are required to determine the effects of these aspects of atmospheric flows and to aid in the interpretation of towing-tank results so that full-scale predictions can can be made.

In a major field study recently completed, Environmental Research and Technology, Inc., under contract to the EPA, collected six-weeks of data on flow and dispersion around a 100 m high, isolated hill (Cinder Cone Butte) in a broad, flat river basin in southwestern Idaho. Detailed measurements were made of wind, turbulence and temperature profiles in the approach flow and at other positions on the hill. SF_6 as a tracer and smoke for flow visualization were released from a mobile crane that allowed flexible positioning of the source height and location. One-hundred samples on the hill collected data on surface concentrations. LIDAR was used to obtain plume trajectories and dimensions. The study concentrated on stable plume impaction.

One particular hour from that field-study data was selected for simu-

lation in the stratified towing tank (Snyder and Lawson, 1981). That hour was 0500 to 0600, October 24, 1980 (Case 206), which may be characterized as very stable, i.e., light winds and strong stable temperature gradients. Measurements made during the towing-tank experiments included glc's under various stabilities and wind directions, vertical distributions of concentration at selected points, plume distributions in the absence of the hill, and visual observations of plume characteristics and trajectories.

This series of tows showed that the surface concentration distributions were extremely sensitive to changes in wind direction. For example, Figure 16 shows that the distribution shifted from the north side of the hill to the south side with a shift of only 5° in wind direction. Comparisons of individual distributions with field results showed very much larger maximum glc's and much narrower distributions in the model results. To account for this variability in the winds measured during the hour, a matrix of 18 tows (3 wind directions x 6 wind speeds) was conducted and the concentration patterns were superimposed. Figure 17, a scatter plot of superposed model concentrations versus field concentrations, showed a marked improvement over the previous single-tow comparisons. The largest model concentrations were within a factor of 2 of the highest field values.

3.5 Limitations of the Towing Tank

In our previous discussions of the dividing-streamline concept, we implicitly assumed that the portion of the flow with insufficient kinetic energy to surmount the hill top was able to pass around the sides of the hill. However, if the model is two-dimensional (spans the width of the tank), the fluid with insufficient kinetic energy is blocked or trapped upstream. Because of continuity, the blocked fluid must conserve its volume. Hence, as the distance between the model and the upstream endwall of the tank

decreases, the blocked fluid is "squashed", i.e., since the length of the blocked region must decrease with distance along the tow, the depth of the fluid that was initially blocked must increase. Eventually, all of the fluid upstream of the model will spill over the top. The fixed end on the tank, in effect, provides a uniform approach flow velocity profile at a distance upstream of the model that varies as the experiment progresses.

Snyder et al (1984) addressed this problem through a series of towing-tank studies. They used a series of "infinite" ridges of quite different cross-sectional shape to test the validity of the "steady-state" assumption of flow upwind of two-dimensional ridges under strongly stratified conditions. Three ridge shapes were used, a vertical fence, a triangular ridge with a slope of 63°, and a Witch of Agnesi ($1/(1+x^2)$) with a maximum slope of 39°.

Results will be shown here only for the triangular ridge. A density sampling rake was positioned 11 hill heights upwind of the ridge and towed with the ridge. Density samples were collected just prior to the start of the tow, during the first and last meter of the tow, and at the one-third and two-thirds points of the tow (the total length of the tow was approximately 20 m). The experiments were conducted at a Froude number of 0.5 (based on the tow speed and the undisturbed density profile), so that the calculated depth of blocked fluid (the dividing-streamline height) was 0.5h.

Figure 18 shows the density profiles collected during the tows. It is clear that the initial near-linear density profile was continuously modified during the tow at a position 11 h upstream and that upstream conditions did not reach a steady state. The profiles tended toward neutral at elevations below half the hill height.

The conclusion from this series of studies was that steady-state conditions are not established in strongly stratified flows (say, $F < 1$) over two-dimensional ridges in finite-length towing tanks. The "approach flow"

velocity and density profiles changed continuously during the tow. Thus, these experiments have no analog in the real atmosphere.

4. CONCLUSIONS

Laboratory measurements of the maximum glc's from elevated sources in the vicinity of two- and three-dimensional terrain features have been presented and compared. Stable conditions produced the highest glc's when the source was located near the dividing-streamline. In this case, the maximum glc was close to the concentration on the plume centerline from an identical release in the absence of the hill. Under neutral conditions, the maximum glc's occurred with the source located just downwind of a two-dimensional ridge. This maximum was found to be about 15 times the maximum glc observed for an identical release over flat terrain.

For practical purposes, a plume released in the upper layer (above the dividing-streamline) in strongly stratified flow over a hill can be treated as a release from a shorter stack upwind of a shorter hill, i.e., as if a ground-plane were inserted at the dividing-streamline height.

A comparison of field and laboratory observations of concentration patterns on a hill surface under strongly stratified conditions showed very good correspondence when wind speed and direction variability were accounted for in the model experiments. Concentration distributions on the hill surface were found to be extremely sensitive to slight changes in wind direction.

Finally, strongly stratified towing-tank experiments on flows over two-dimensional ridges were found to have no analog in the real atmosphere because of the unsteadiness created by the finite length of the tank.

REFERENCES

Arya, S.P.S. and Shipman, M.S., 1981: An Experimental Investigation of Flow and Diffusion in the Disturbed Boundary Layer over a Ridge; Part I: Mean Flow and Turbulence Structure, Atmos. Envir. v. 15, no. 7, p.1173-1184.

Arya, S.P.S., Shipman, M.S. and Courtney, L.Y., 1981: An Experimental Investigation of Flow and Diffusion in the Disturbed Boundary Layer over a Ridge; Part II: Diffusion from a Continuous Point Source, Atmos. Envir., v. 15, no. 7, p. 1185-1194.

Bass, A., Strimaitis, D.G. and Egan, B.A., 1981: Potential Flow Model for Gaussian Plume Interaction with Simple Terrain Features, Rpt. to Envir. Prot. Agcy. under Contract No. 68-02-2759, Res. Tri. Pk., NC, 201p.

Britter, R.E., Hunt, J.C.R., Marsh, G.L. and Snyder, W.H., 1983: The Effects of Stable Stratification on Turbulent Diffusion and the Decay of Grid Turbulence, J. Fluid Mech., v. 127, p. 27-44.

Castro, I.P. and Snyder, W.H., 1982: A Wind Tunnel Study of Dispersion from Sources Downwind of Three-Dimensional Hills, Atmos. Envir., v. 16, no. 8, p. 1869-87.

Castro, I.P., Snyder, W.H. and Marsh, G.L., 1983: Stratified Flow over Three-Dimensional Ridges, J. Fluid Mech., v. 135, p. 261-82.

Courtney, L.Y. and Arya, S.P.S., 1980: Boundary Layer Flow and Diffusion over a Two-dimensional Low Hill, Reprints Vol., Second Joint Conf. on Appl. of Air Poll. Meteorol., Mar. 24-28, New Orleans, LA, Amer. Meteorol. Soc., Boston, MA, p. 551-8.

Egan, B.A., 1975: Turbulent Diffusion in Complex Terrain, Workshop on Air Poll. Meteorol. and Envir. Assess., Amer. Meteorol. Soc., Sept. 30-Oct. 3, Boston, MA.

Hunt, J.C.R., Puttock, J.S. and Snyder, W.H., 1979: Turbulent Diffusion from a Point Source in Stratified and Neutral Flows around a Three-Dimensional Hill: Part I: Diffusion Equation Analysis, Atmos. Envir., v. 13, p. 1227-39.

Hunt, J.C.R., Richards, K.J. and Brighton, P.W.M., 1984: Stratified Shear Flow over Low Hills: II. Stratification Effects in the Outer Flow Region, To be submitted to Quart. J. Roy. Meteorol. Soc.

Hunt, J.C.R. and Snyder, W.H., 1980: Experiments on Stably and Neutrally Stratified Flow over a Model Three-Dimensional Hill, J. Fluid Mech., v. 96, pt. 4, p. 671-704.

Khurshudyan, L.H., Snyder, W.H. and Nekrasov, I.V., 1981: Flow and Dispersion of Pollutants over Two-Dimensional Hills: Summary Report on Joint Soviet-American Study, Envir. Prot. Agcy. Rpt. No. EPA-600/4-81-067, Res. Tri. Pk., NC., p. 143.

Pasquill, F., 1974: Atmospheric Diffusion, 2nd Ed., Chichester, Ellis Horwood Ltd., John Wiley and Sons, NY, NY, p. 429.

Snyder, W.H., 1979: The EPA Meteorological Wind Tunnel: Its Design, Construction, and Operating Characteristics, Envir. Prot. Agcy. Rpt. No. EPA-600/4-79-051, Res. Tri. Pk., NC, p. 78.

Snyder, W.H., 1981: Guideline for Fluid Modeling of Atmospheric Diffusion, Envir. Prot. Agcy. Rpt. No. EPA-600/8-81-009, Res. Tri. Pk., NC, p. 200.

Snyder, W.H. and Britter, R.E., 1979: Aspect Ratio Study, Unpublished Data Report, Fluid Modeling Facility, Envir. Prot. Agcy., Res. Tri. Pk., NC.

Snyder, W.H., Britter, R.E. and Hunt, J.C.R., 1980: A Fluid Modeling Study of the Flow Structure and Plume Impingement on a Three-Dimensional Hill in Stably Stratified Flow, Proc. Fifth Int. Conf. on Wind Engr. (J.E. Cermak, ed.), v. 1, p. 319-29, Pergamon Press, NY, NY.

Snyder, W.H. and Hunt, J.C.R., 1984: Turbulent Diffusion from a Point Source in Stratified and Neutral Flows around a Three-Dimensional Hill; Part II: Laboratory Measurements of Surface Concentrations, Atmos. Envir. (to appear).

Snyder, W.H. and Lawson, R.E. Jr., 1981: Laboratory Simulation of Stable Plume Dispersion over Cinder Cone Butte: Comparison with Field Data, in EPA Complex Terrain Modeling Program, First Milestone Report - 1982, Rpt. No. EPA-600/3/82-036, Envir. Prot. Agcy., Res. Tri. Pk., NC, p. 250-304.

Snyder, W.H. and Lawson, R.E., Jr., 1983: Stable Plume Dispersion over an Isolated Hill: Releases above the Dividing-Streamline Height, Unpublished report, Fluid Modeling Facility, Envir. Prot. Agcy., Res. Tri. Pk., NC.

Snyder, W.H., Thompson, R.S., Eskridge, R.E., Lawson, R.E., Jr., Castro, I.P., Lee, J.T., Hunt, J.C.R. and Ogawa, Y., 1983: The Structure of Strongly Stratified Flow over Hills: Dividing-Streamline Concept, Submitted to J. Fluid Mech.

Thompson, R.S. and Snyder, W.H., 1976: EPA Fluid Modeling Facility, Proc. Conf. on Modeling and Simulation, Rpt. No. EPA-600/9-76-016, Envir. Prot. Envir. Agcy., Wash. D.C., July.

Weil, J.C., Traugott, S.C. and Wong, D.K., 1981: Stack Plume Interaction and Flow Characteristics for a Notched Ridge, Rpt. No. PPRP-61, Maryland Power Plant Siting Program, Martin Marietta Corp., Baltimore, MD, p. 92.

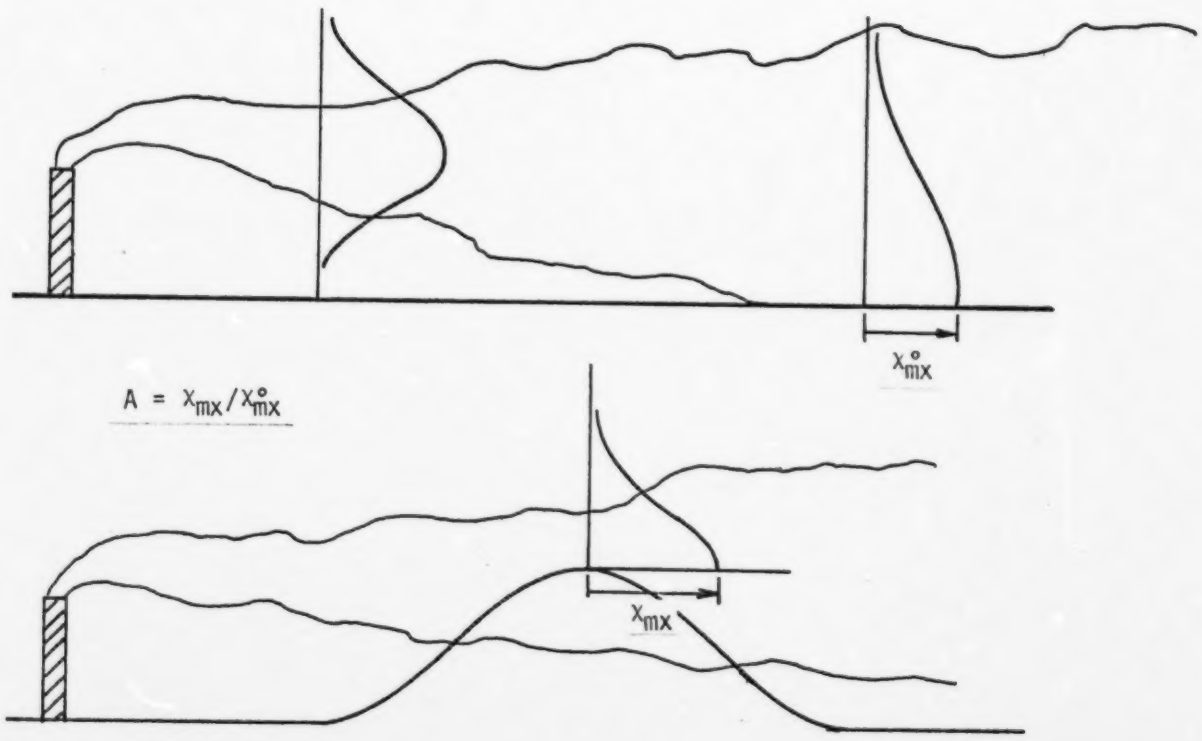


Figure 1. Definition of terrain amplification factor, A.

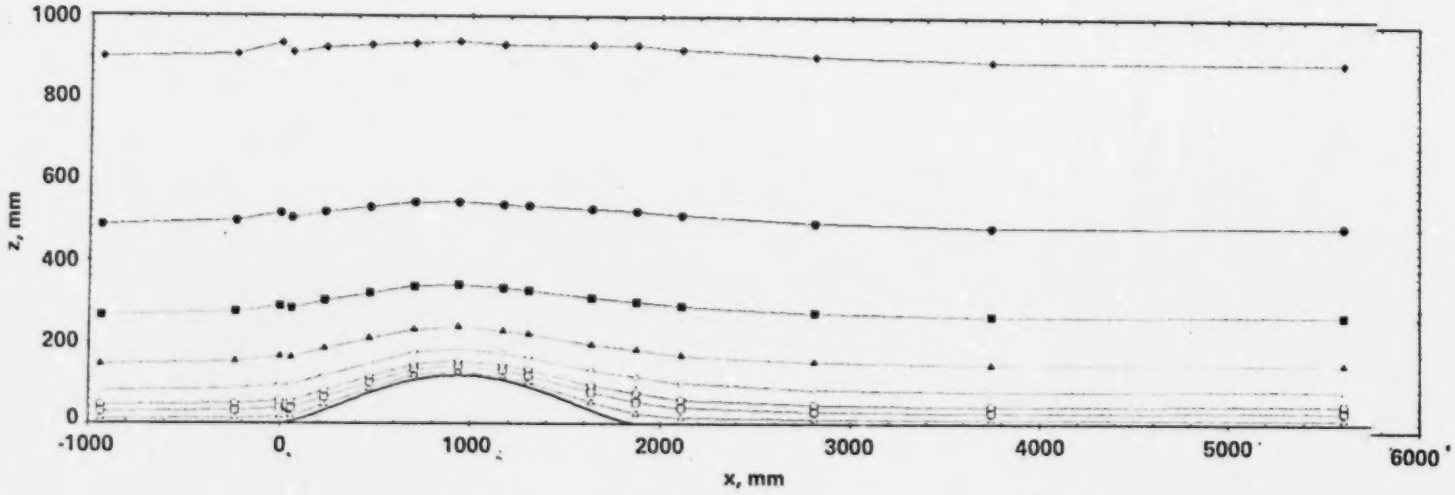


Figure 2. Streamline pattern over hill 8 from experimental data.

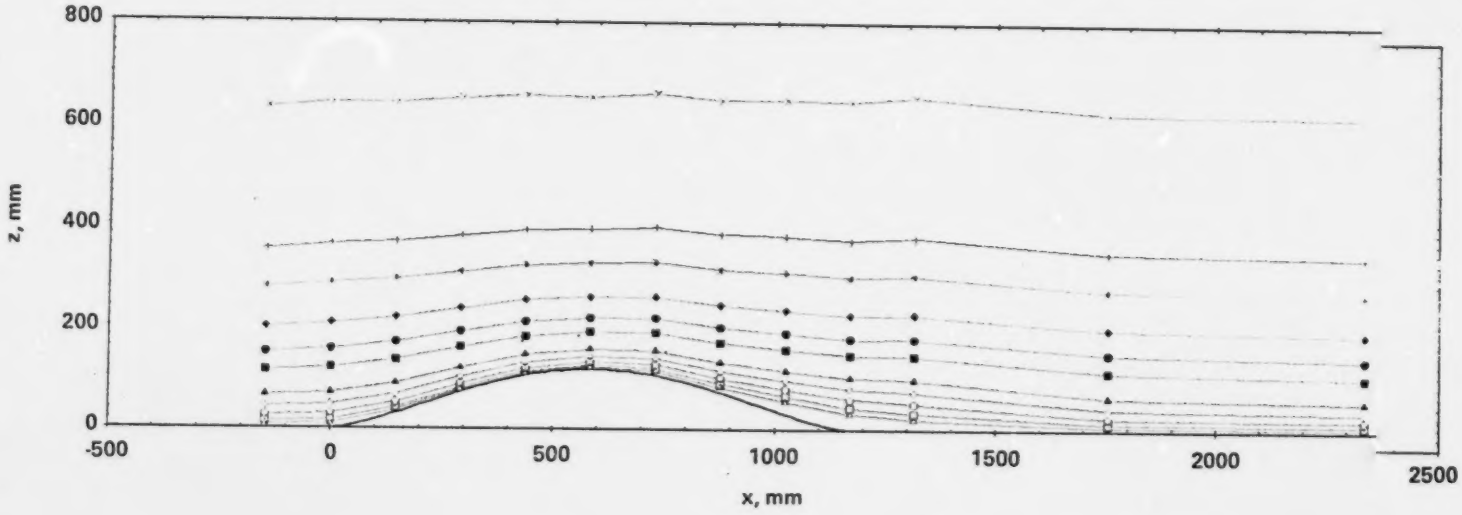


Figure 3. Streamline pattern over hill 5 from experimental data.

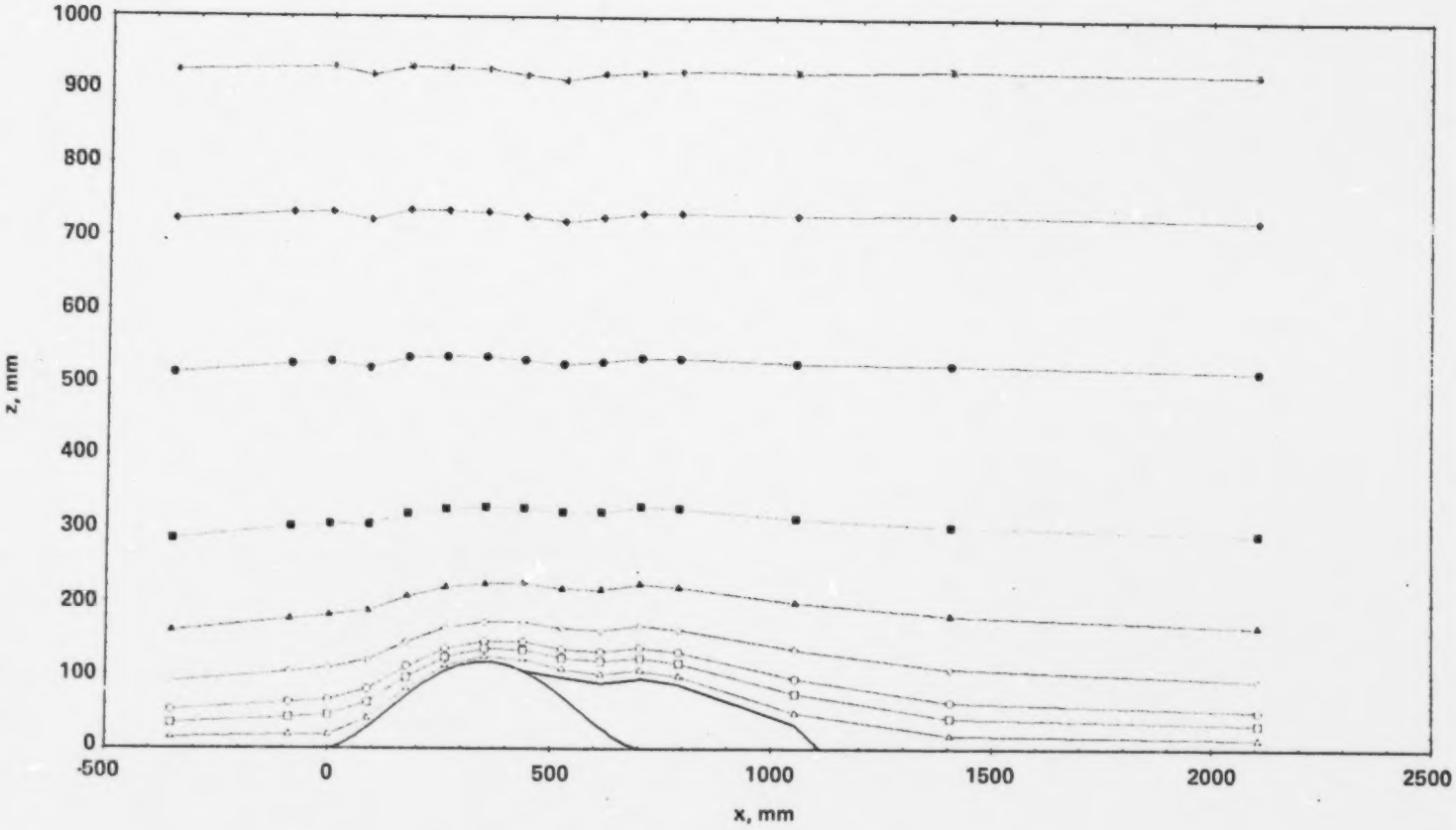


Figure 4. Streamline pattern over hill 3 from experimental data.

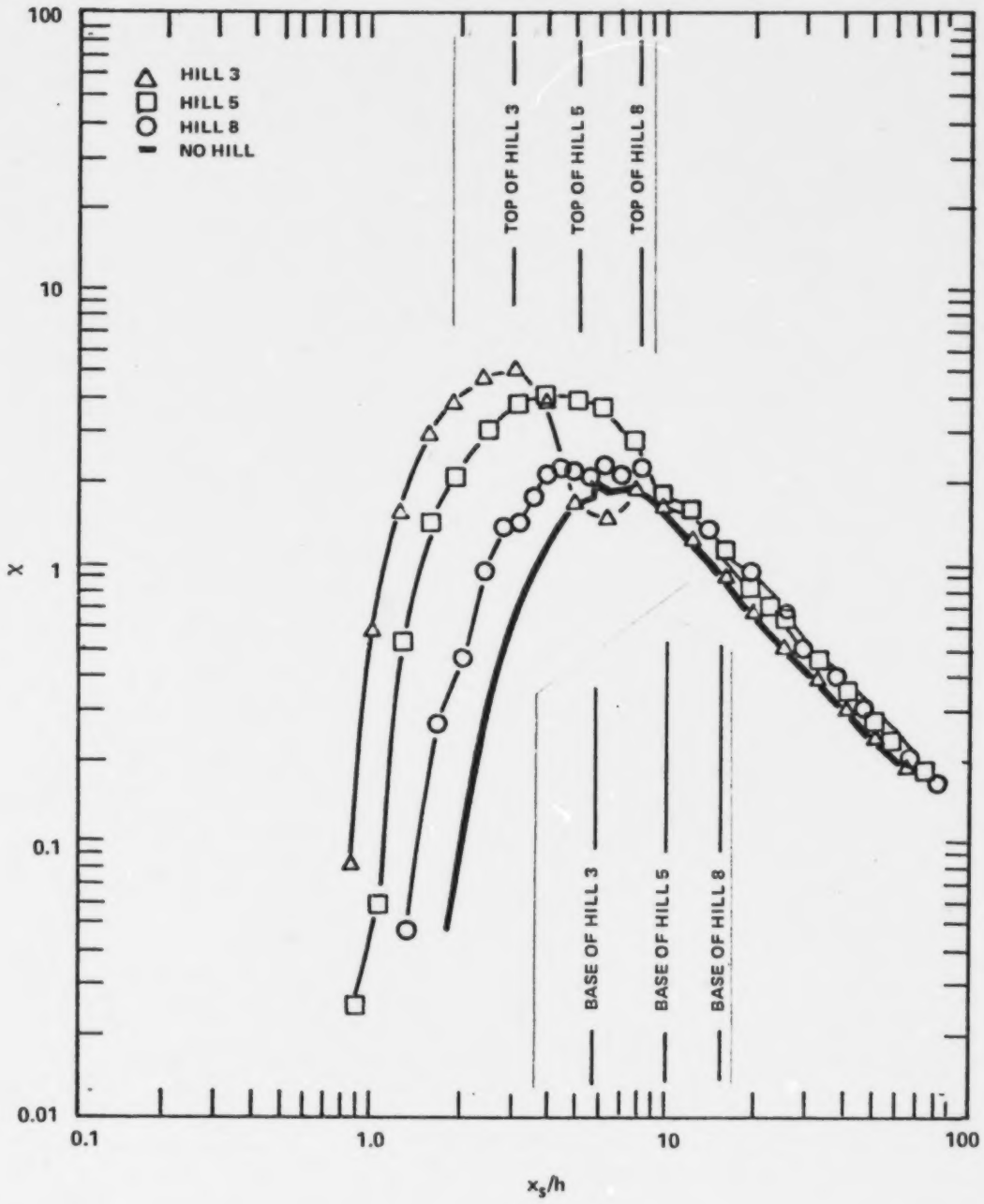


Figure 5. Surface concentration profiles over hills; Upwind base stack location; $H_s/h = 0.5$.

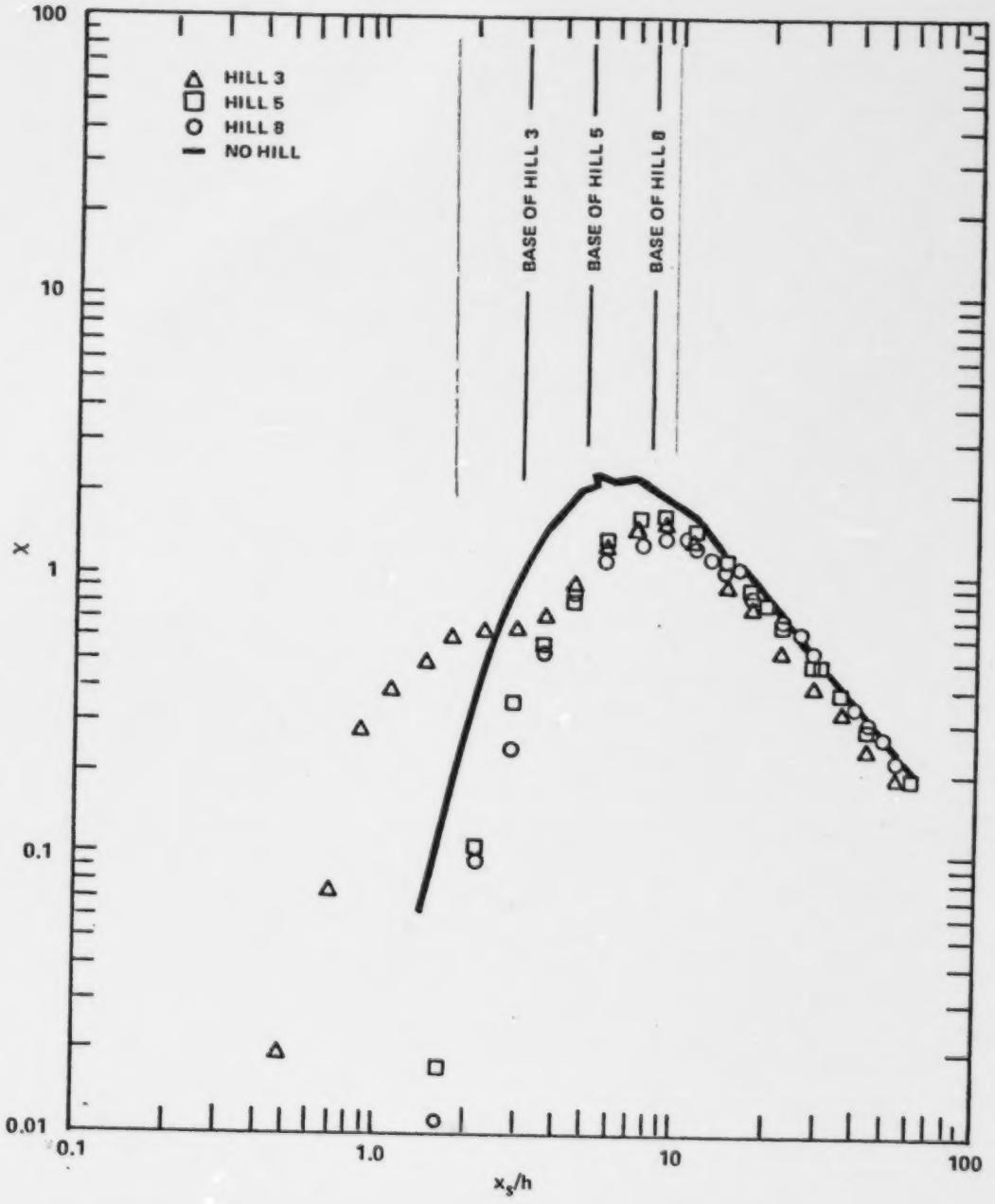


Figure 6. Surface concentration profiles over hills; Hill top stack location; $H_s/h = 0.5$.

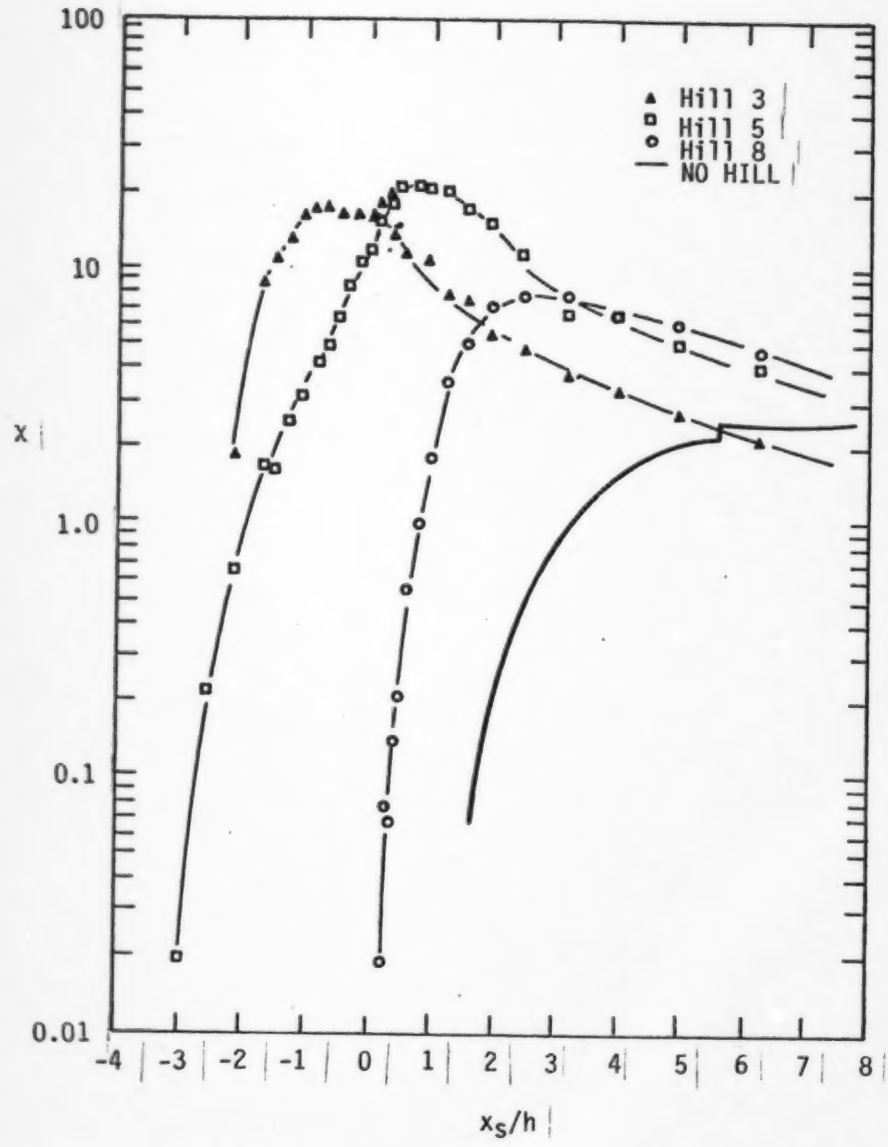
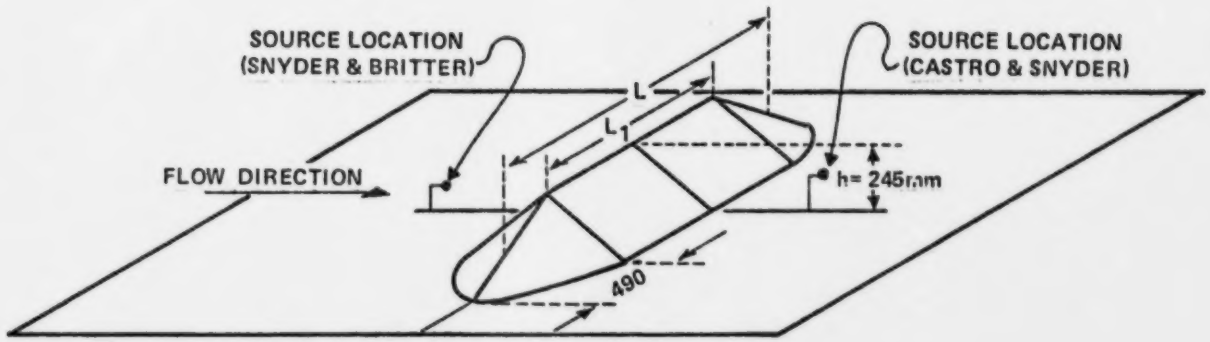


Figure 7. Surface concentration profiles over hills; Downwind base stack location; $H_s/h = 0.5$.



HILL

	C2	C4	C6	CX
L_1, cm	0	45	90	∞
L, cm	49	94	139	∞
L/h	1.9	3.7	5.6	∞

Figure 8. Geometry of triangular hills of different aspect ratio.

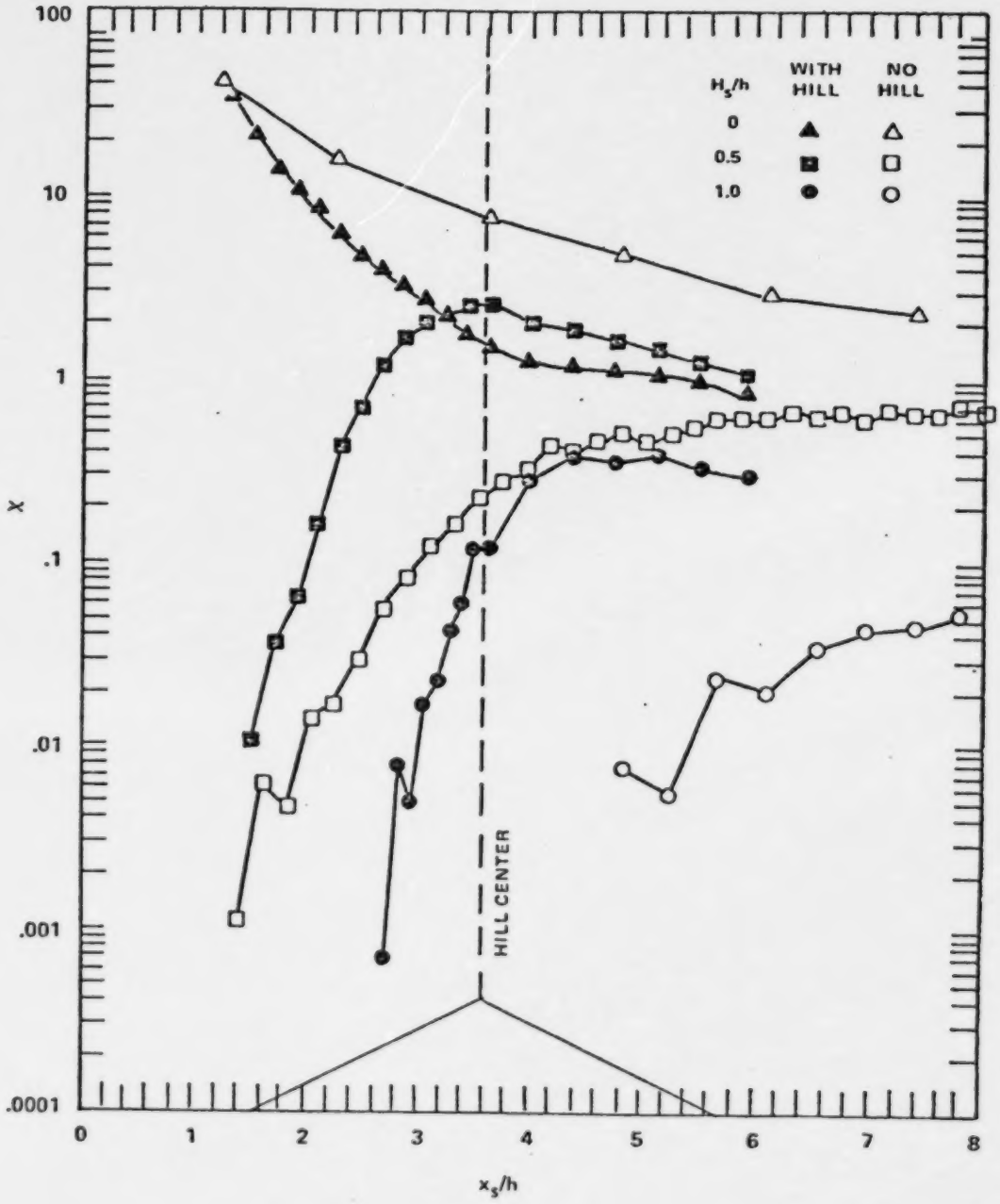


Figure 9. Surface concentrations on hill C2.

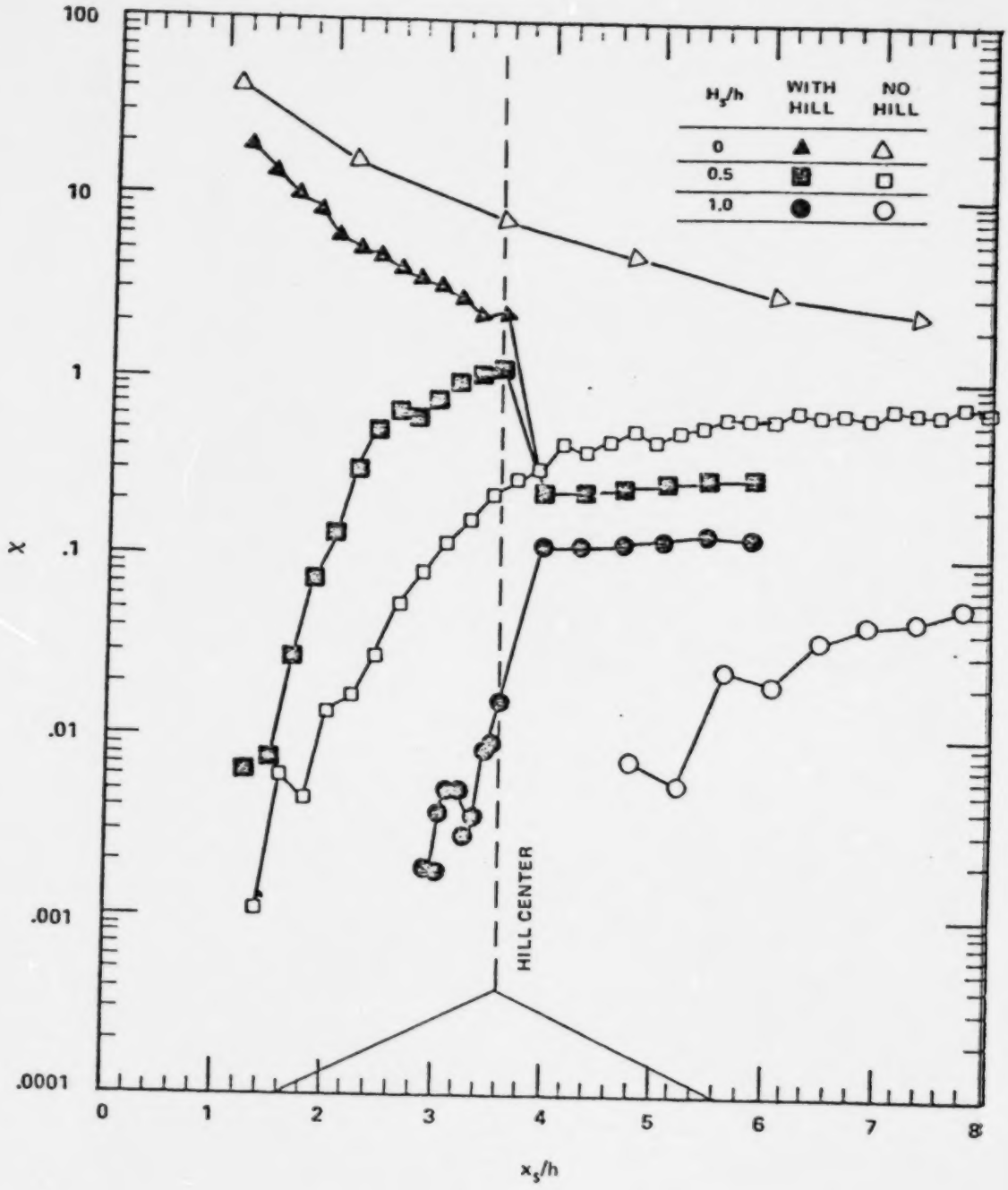


Figure 10. Surface concentrations on hill CX.

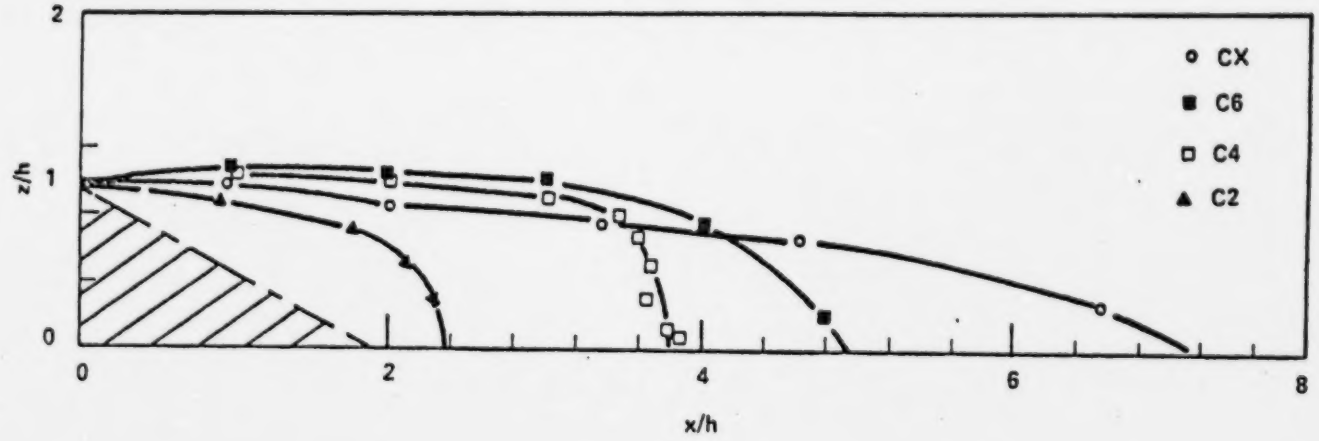


Figure 11. Loci of zero-longitudinal mean velocity on the centerline of hills of different crosswind aspect ratio.

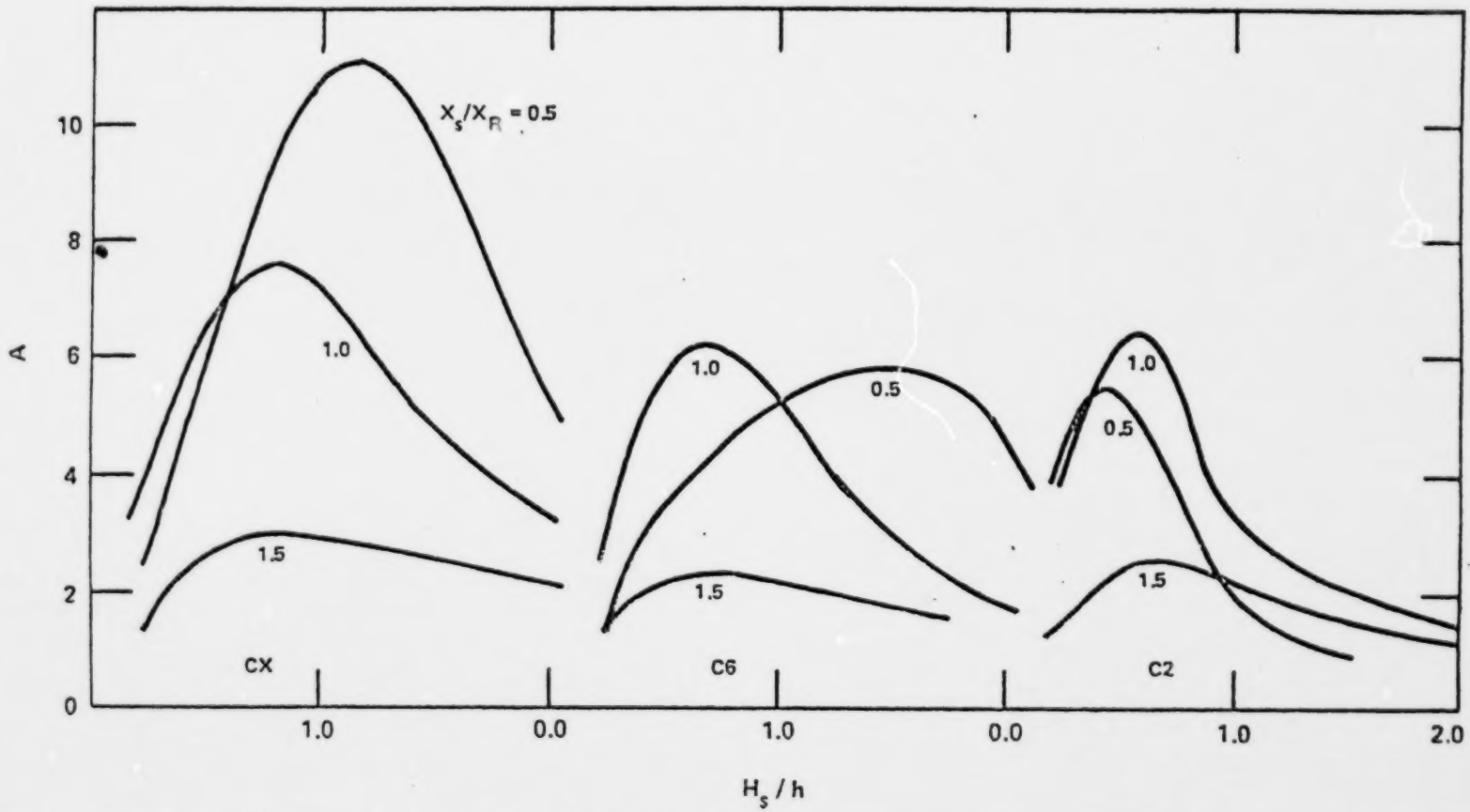


Figure 12. Variation of terrain amplification factor with stack height for hills of different crosswind aspect ratio and downwind sources.

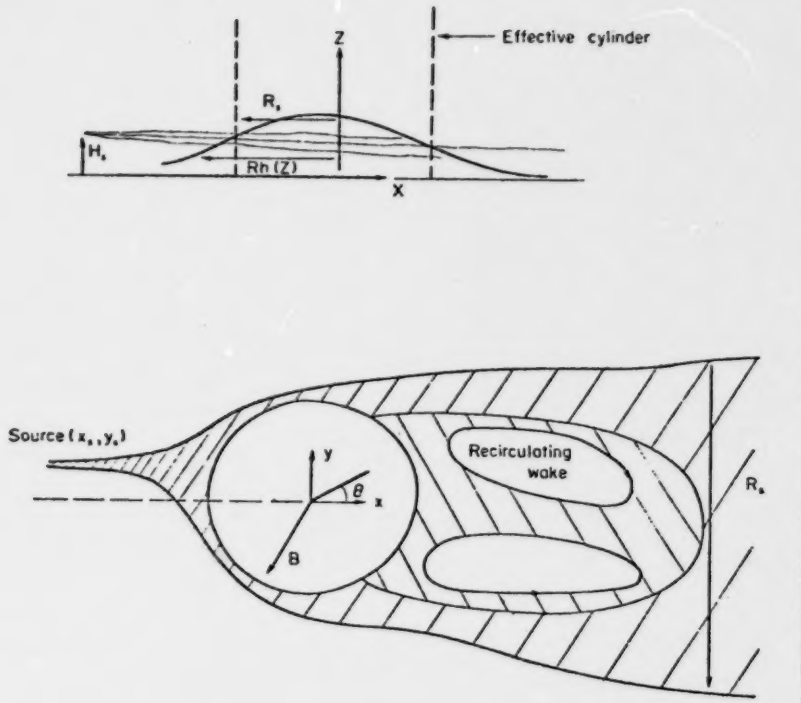


Figure 13. Schematic showing treatment of strongly stratified flow around a hill as potential flow about a cylinder.

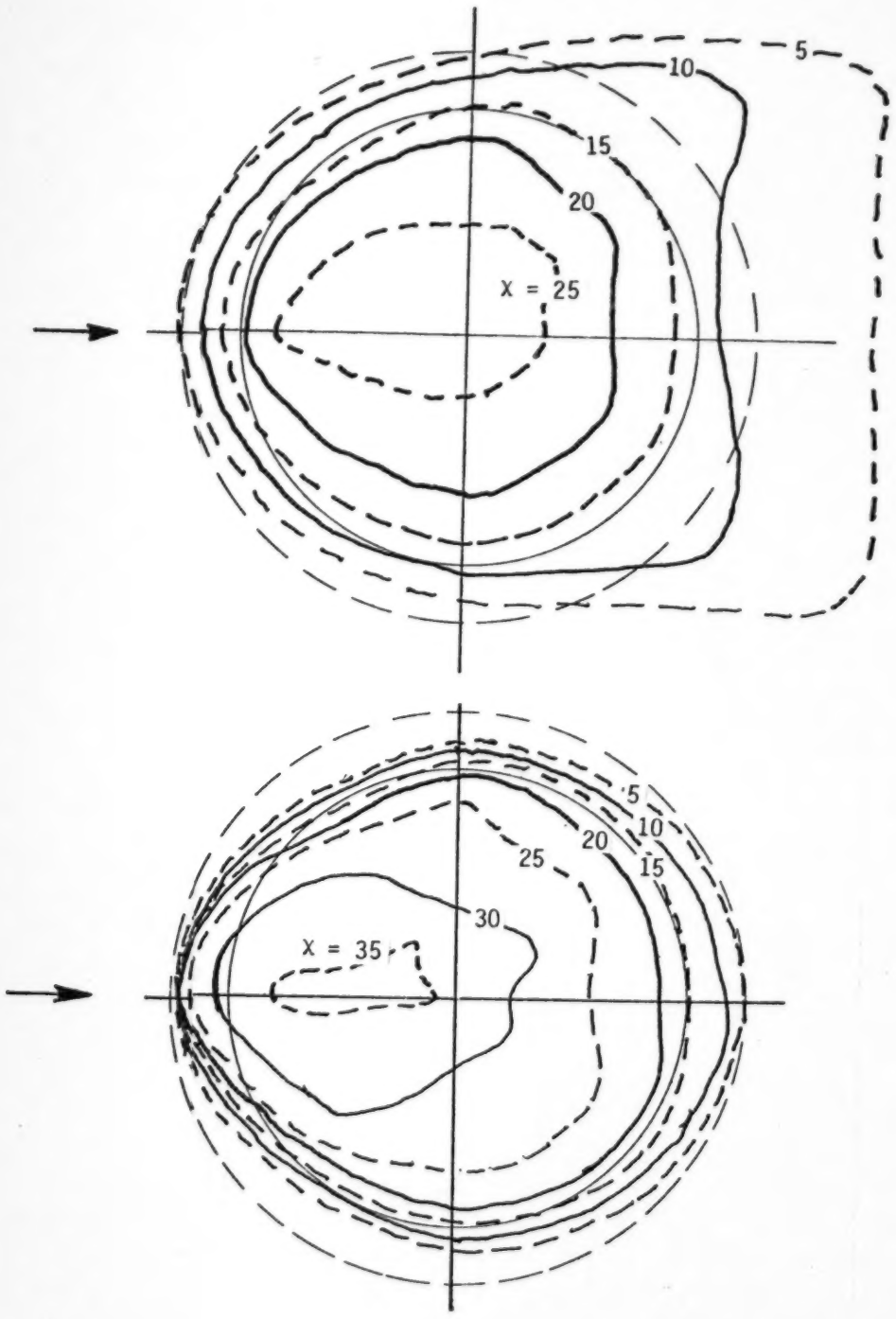


Figure 14. Concentration distributions measured on the hill surface. F = 0.5, H_s/h = 0.6. Top: fully submerged; Bottom: half submerged.

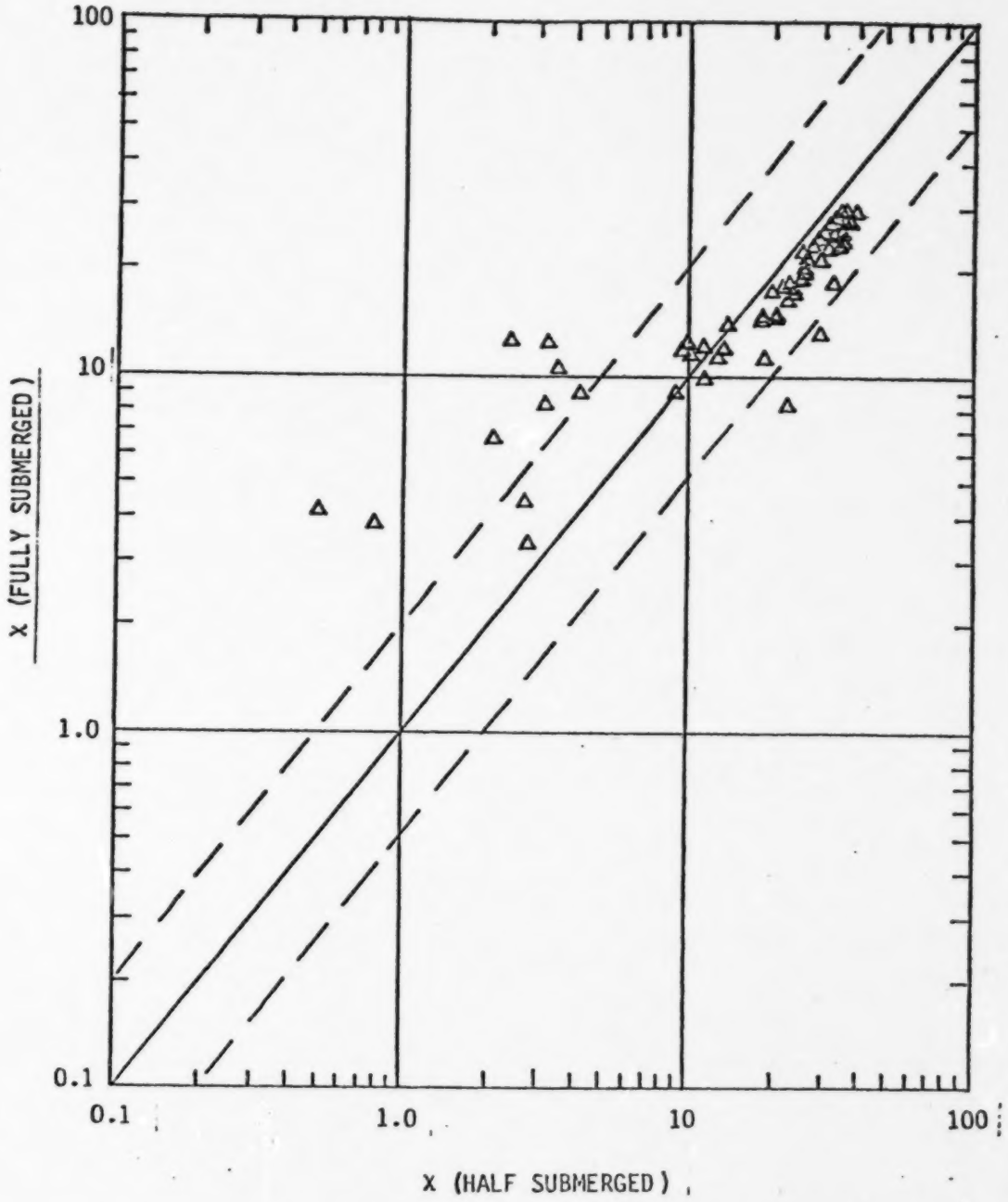


Figure 15. Comparison of concentrations. Half submerged versus fully submerged. $F = 0.5$, $H_s/h = 0.6$.

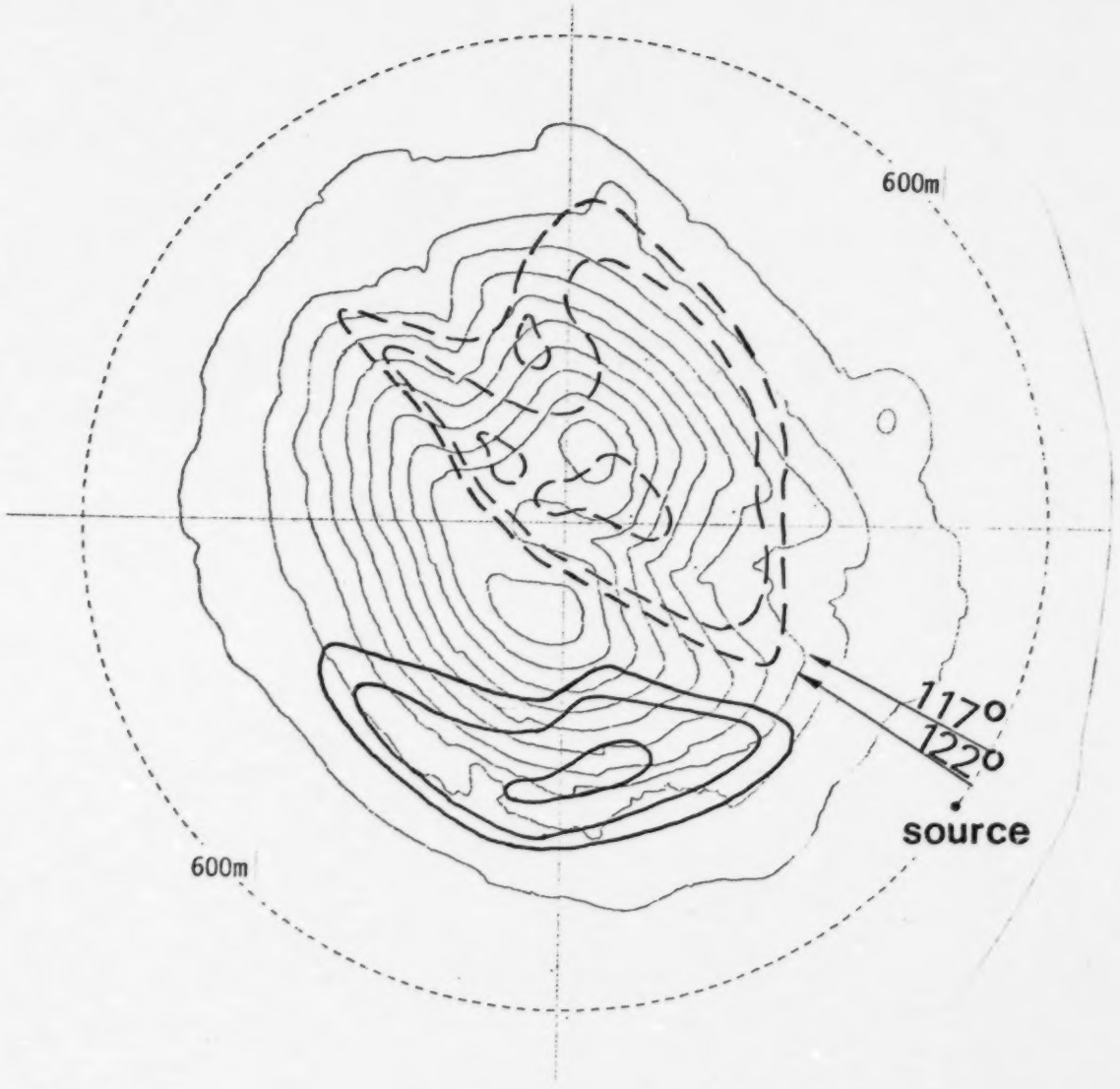


Figure 16. Concentration distributions measured during individual tows: $H_S/h = 0.31$, $H_D/h = 0.38$; Wind direction: —— 117°, ---122°.

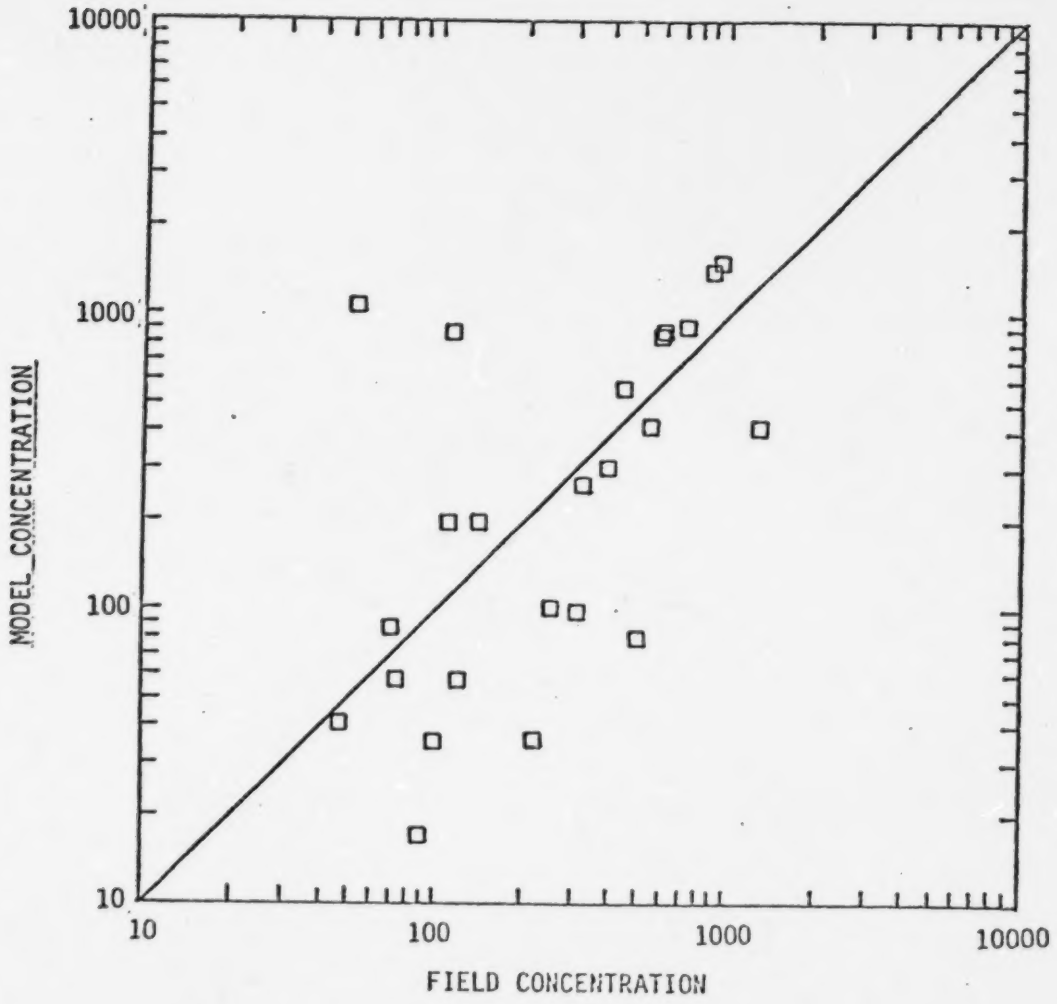


Figure 17. Scatter diagram comparing superposition of concentration distributions from 18 tows with field distributions.

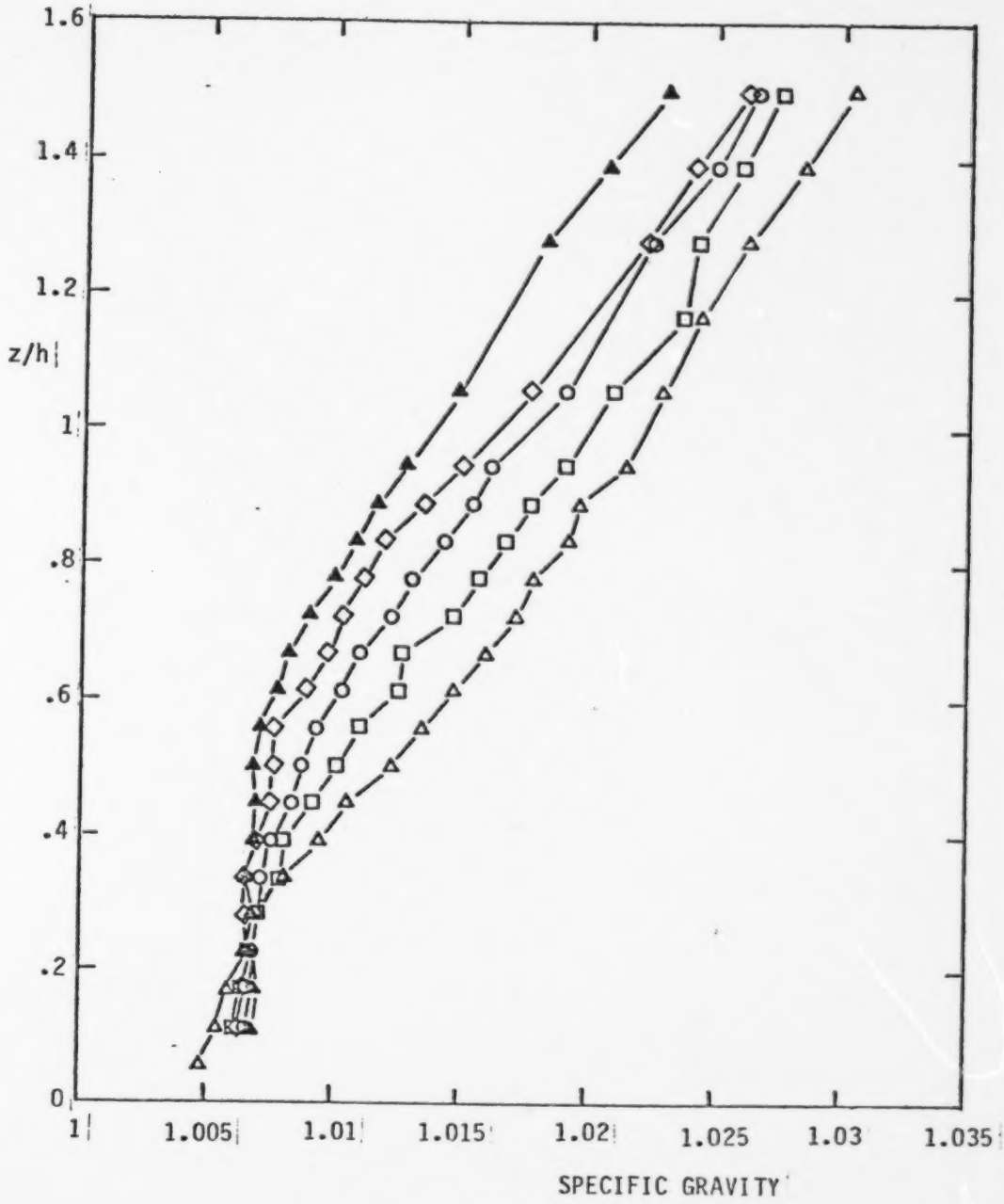


Figure 18. Density profiles measured 11 hill heights upstream of two-dimensional triangular ridge. △, initial density profile. Sampling interval centered at x=: □, 1.3m; ○, 6.7m; ◇, 11.8m; and ▲, 17.7m from start of tow.